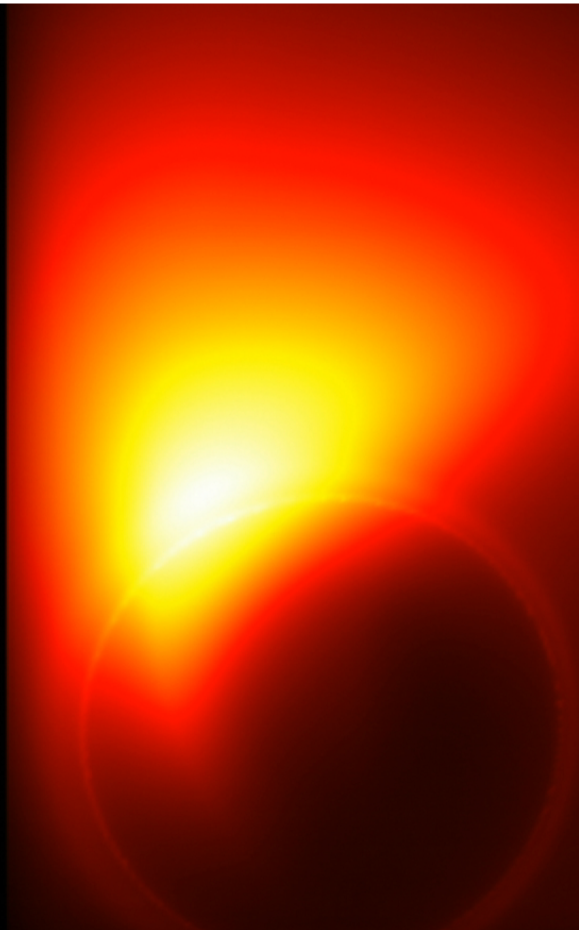
Title: EHT Constraints on Jet Launching in M87

Date: Nov 11, 2014 02:55 PM

URL: http://pirsa.org/14110082

Abstract: Because of the existence of a prominent jet, M87 provides an ideal source with which the EHT can critically test current jet launching paradigms. The EHT has already placed weak limits on the black hole spin based on generic arguments regarding limits on the image size. However, careful modeling of the jet structure can produce much more stringent constraints on both the black hole properties and the mechanisms responsible for the generation of the observed radio emission. I will describe how this modeling is performed, what the remaining chief uncertainties are and why we believe they can be controlled, and how existing EHT observations of M87 support models of electromagnetically launched jets powered by black hole spin.

EHT CONSTRAINTS ON JET LAUNCHING IN M87



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Vincent Fish (MIT Haystack)
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Avi Loeb (Harvard)
Ramesh Narayan (Harvard)
Alexander Tchekhovskoy (Berkeley)
+ EHT Collaboration

UNIVERSITY OF WATERLOO

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

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M87 FACT SHEET

- $M \sim 6.4 \times 10^9 M_\odot$, $D \sim 16.9$ Mpc
  (cf. Kayhan Gultekin's & Jonelle Walsh's talks!)

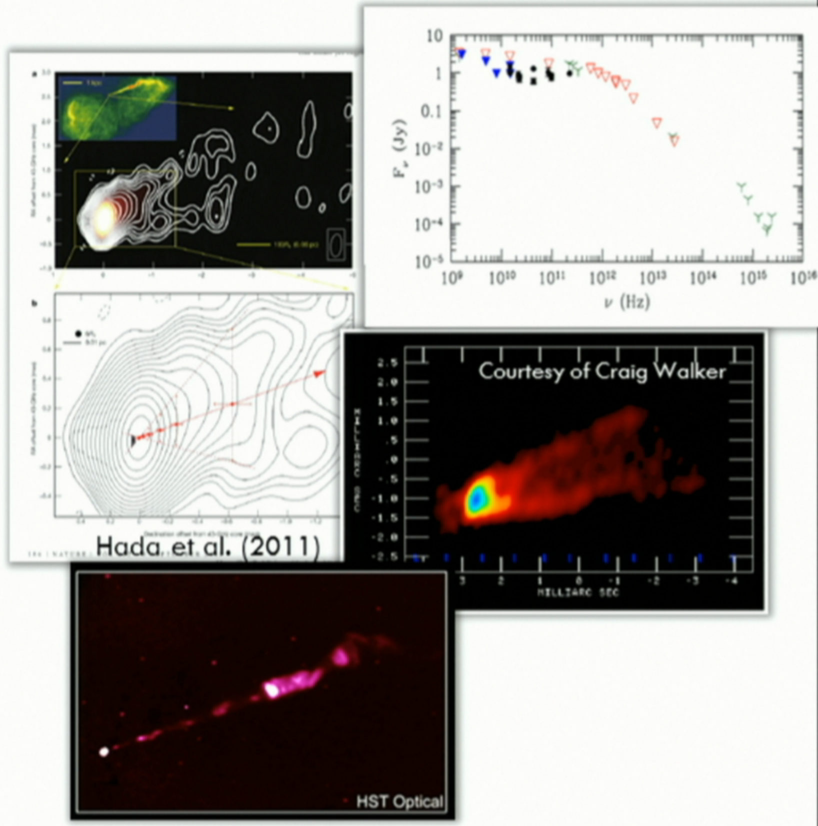
  → $\Delta\theta \sim 38\mu as$

- $L \sim 10^{-6} L_{Edd}$, breaking in mm
- λ-dependent size
- Short timescale variability!

  → Near horizon visible

- Super-luminal motion
  (~2.3c at few mas, ~6c at >1")

- Orientation of large-scale jet (E-W)
- Core Dominance



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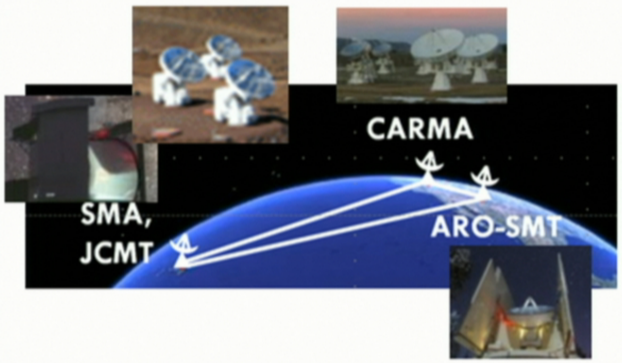
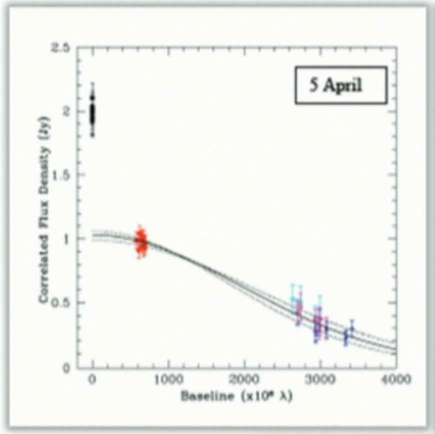
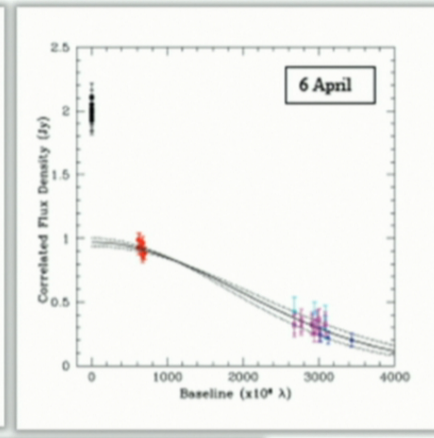
EHT OBSERVATIONS OF M87

Doeleman et al., Science, 338, 355 (2012)





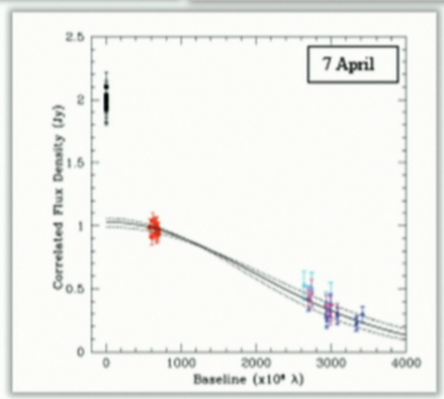


Key Differences from Sgr A*

- **No scattering!**
- **Clear extended jet!**

Key Similarities

- **Horizon-scale structure:** $D \sim 40.0 \pm 0.6\ \mu as$



THEN, NOW, AND …

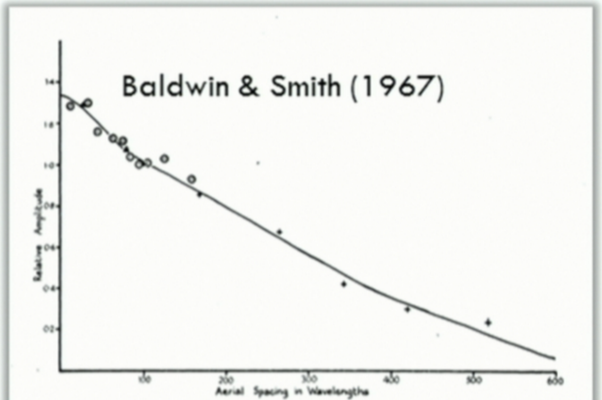


FIG. 1. VISIBILITY-SPACING CURVE FOR M87

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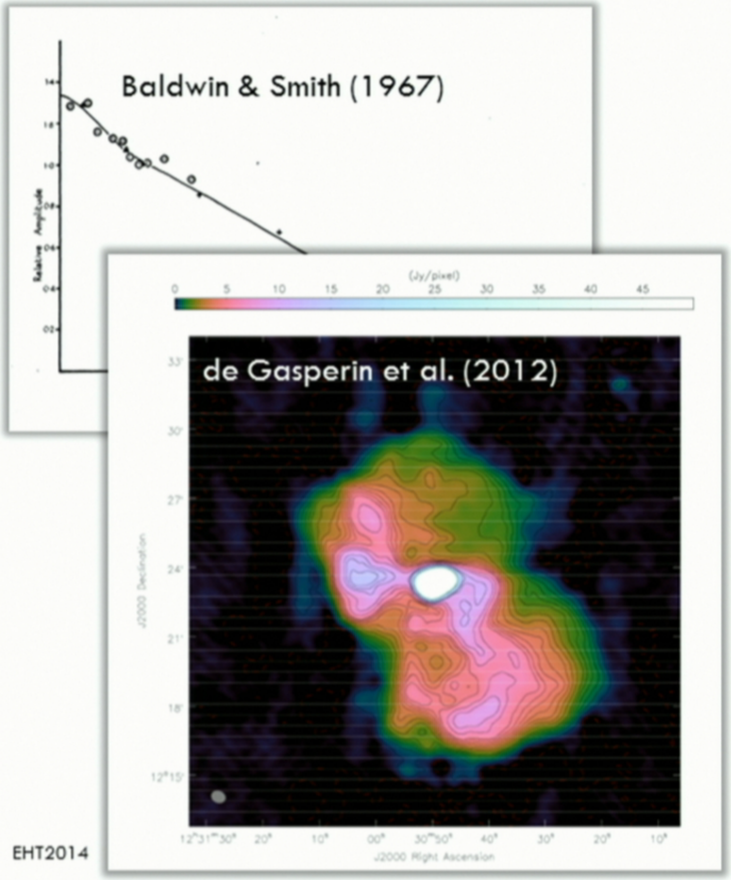
THEN, NOW, AND …



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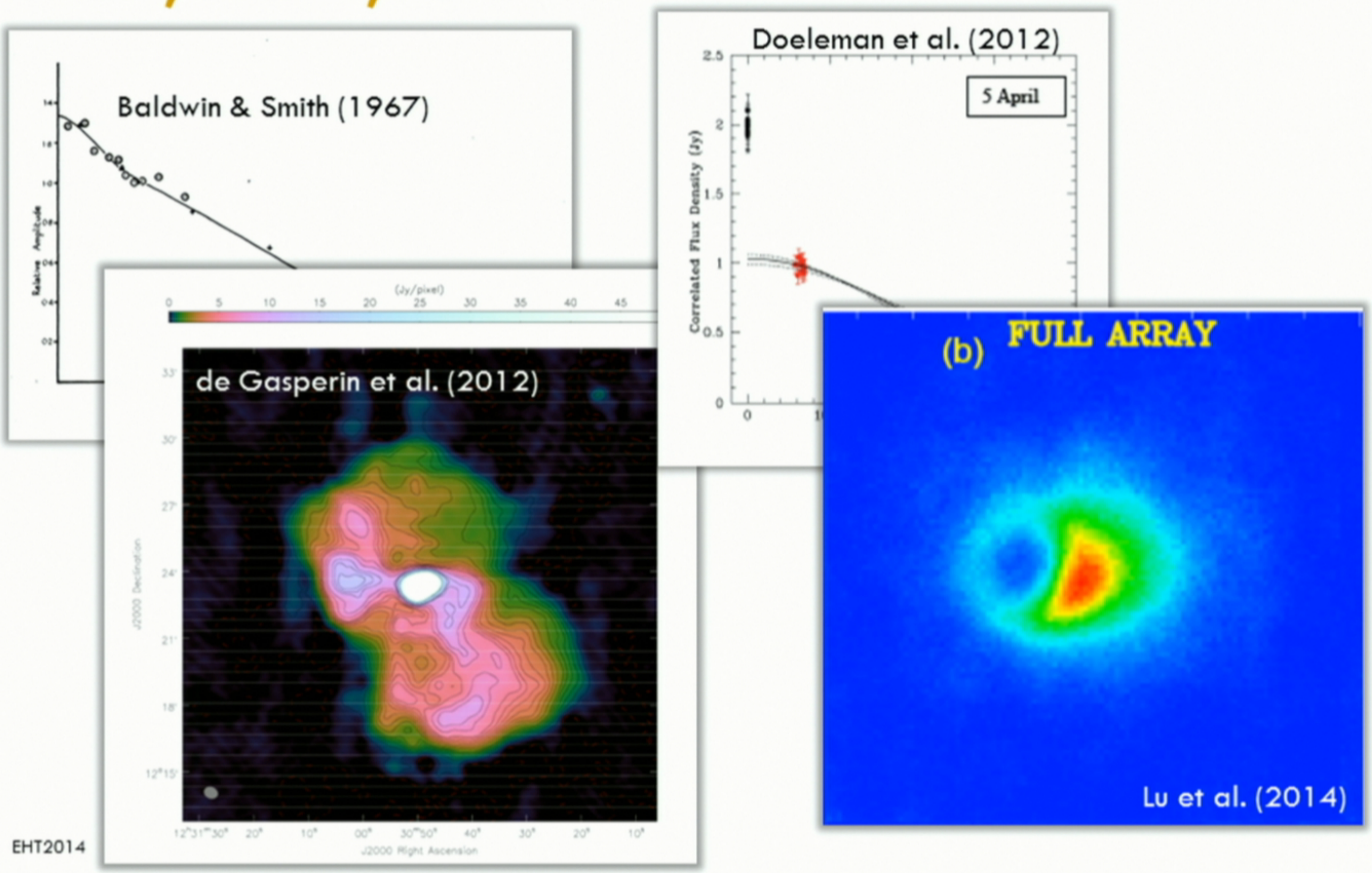

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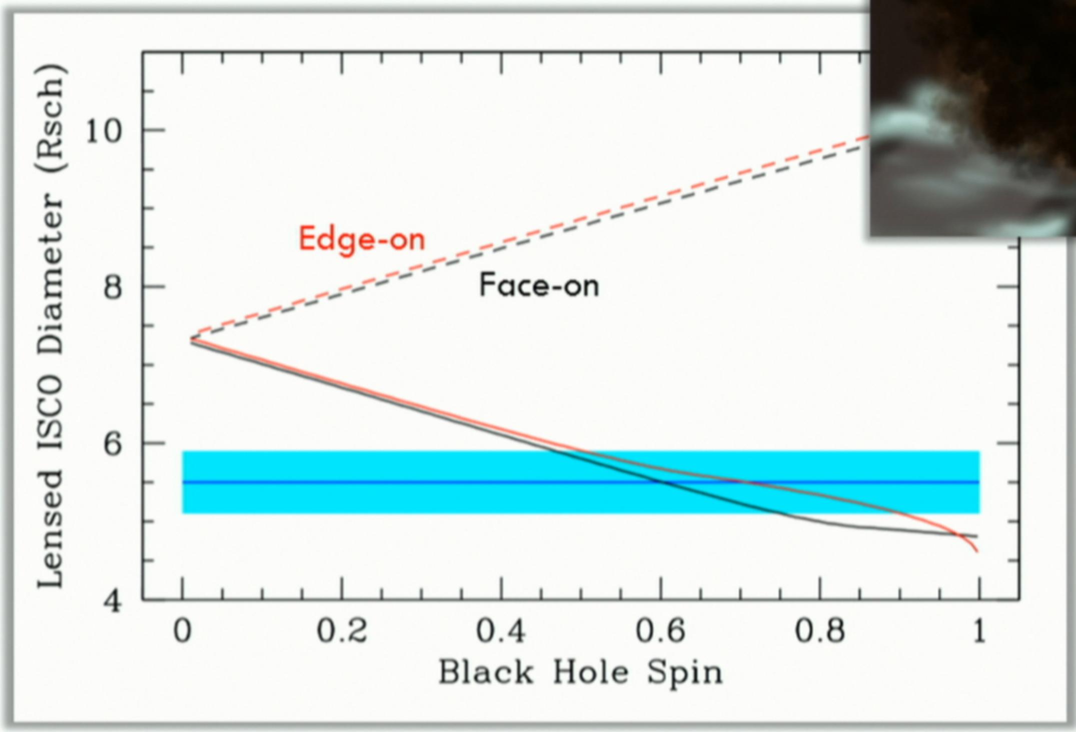
GENERIC LIMITS ON SPIN

Doeleman et al., Science, 338, 355 (2012)



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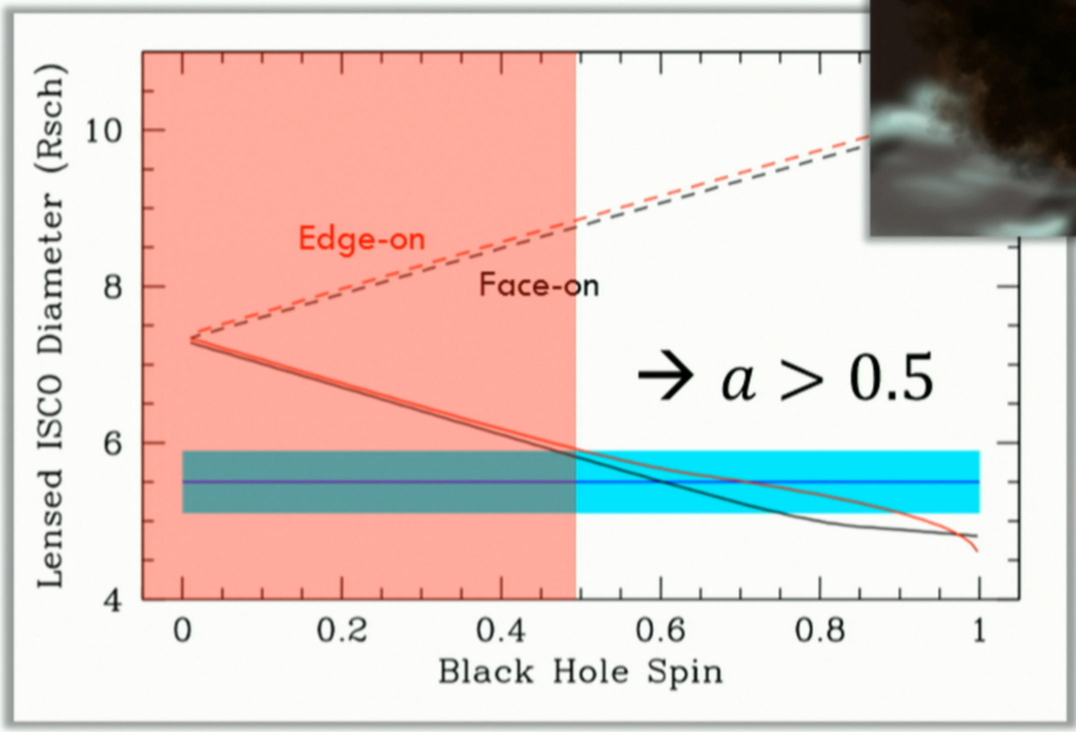

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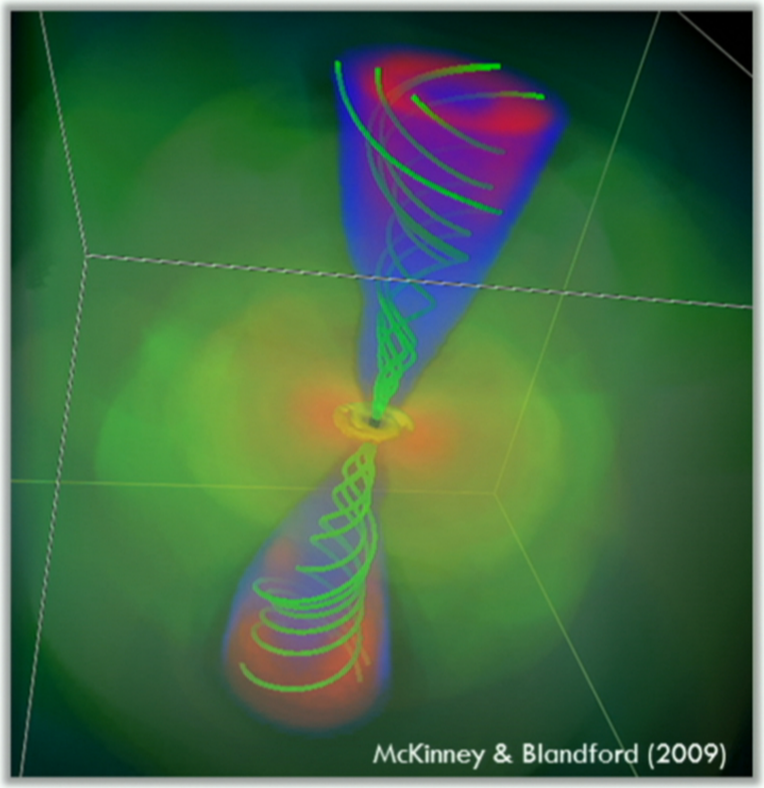
"COMPLICATED" JET MODELS



- **Blanford-Znajek/Blandford-Payne:** **Electromagnetic extraction of black hole spin/disk angular momentum.**
- **Large-scale ordered magnetic fields**
- **Canonical Structure:**
    - MHD Disk
    - Magnetically dominated wind
    - Force-free, roughly parabolic jet

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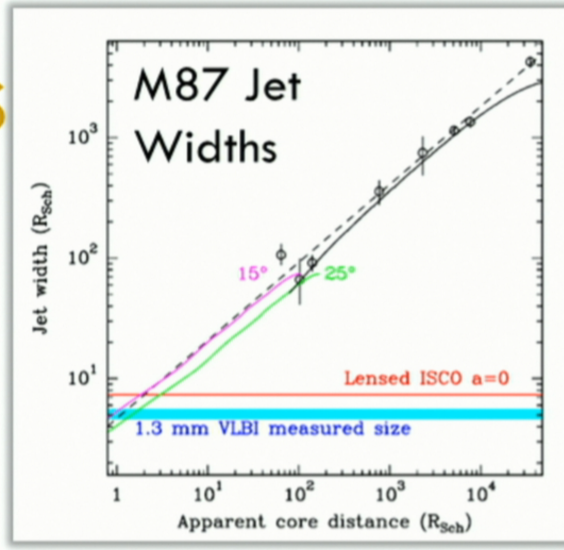

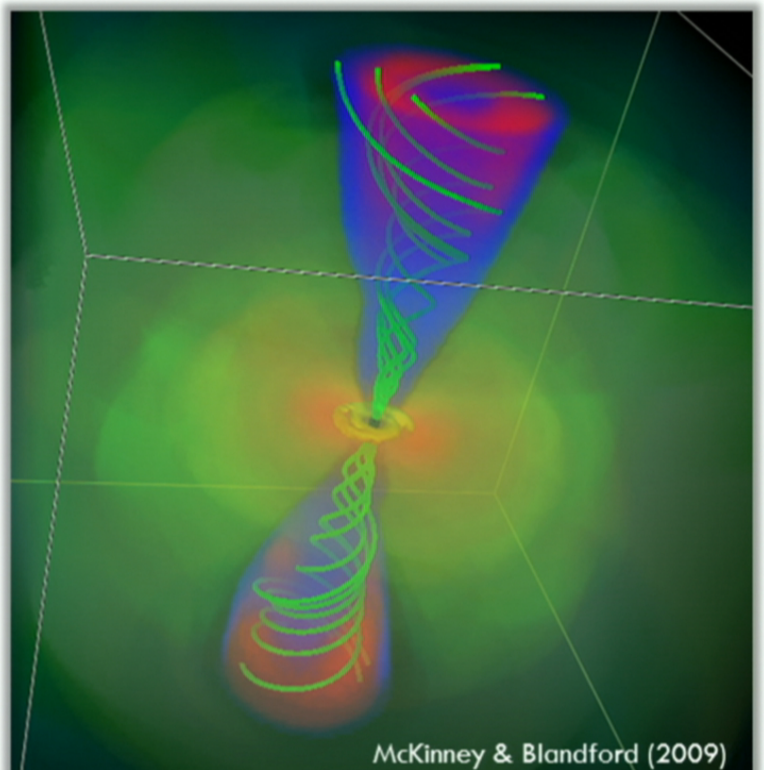

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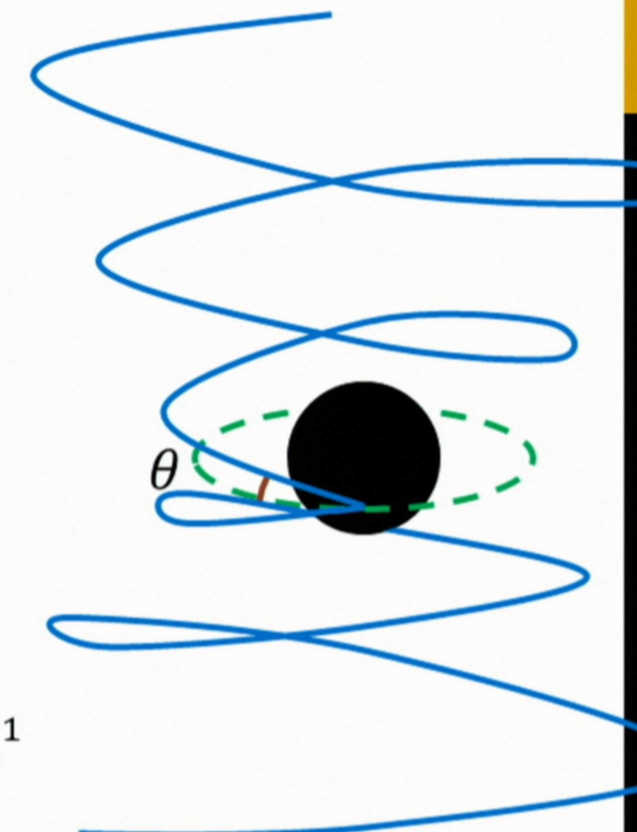
"SIMPLE" JET MODELS

- **Axisymmetric & Stationary (+poloidal struc)**
- **Particle inertia irrelevant:**

$$\boldsymbol{F}_L = \rho \boldsymbol{E} + \boldsymbol{j} \times \boldsymbol{B} = 0$$

- **+ Boundary conditions at disk/black hole!**

$$\Omega_{\text{field}}(r) \text{ and } \tan\theta \sim \frac{v_A}{R\Omega} \sim \frac{B^P}{B^\phi} \sim \beta_\infty^{-1}$$



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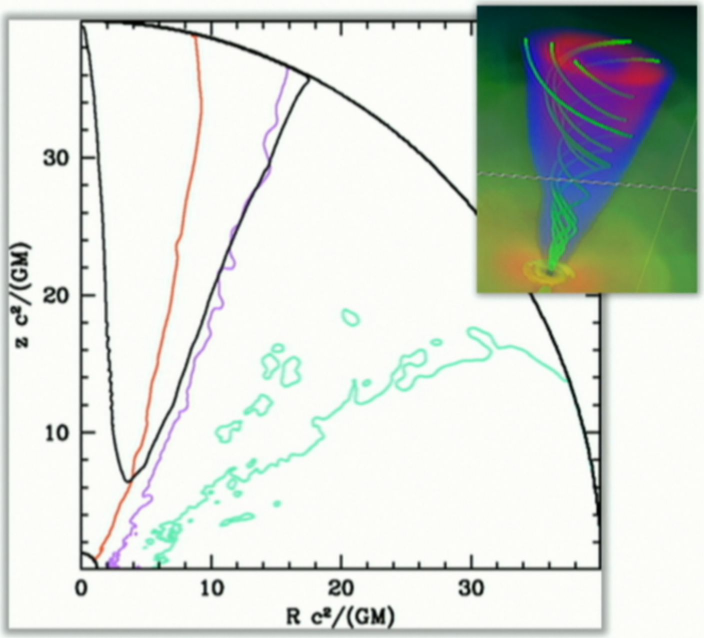
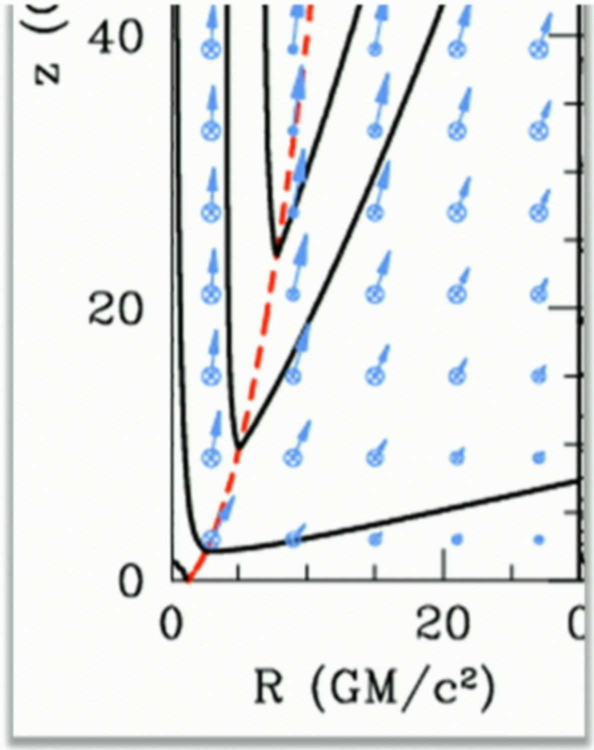
FULL MHD VS. SIMPLE FORCE FREE





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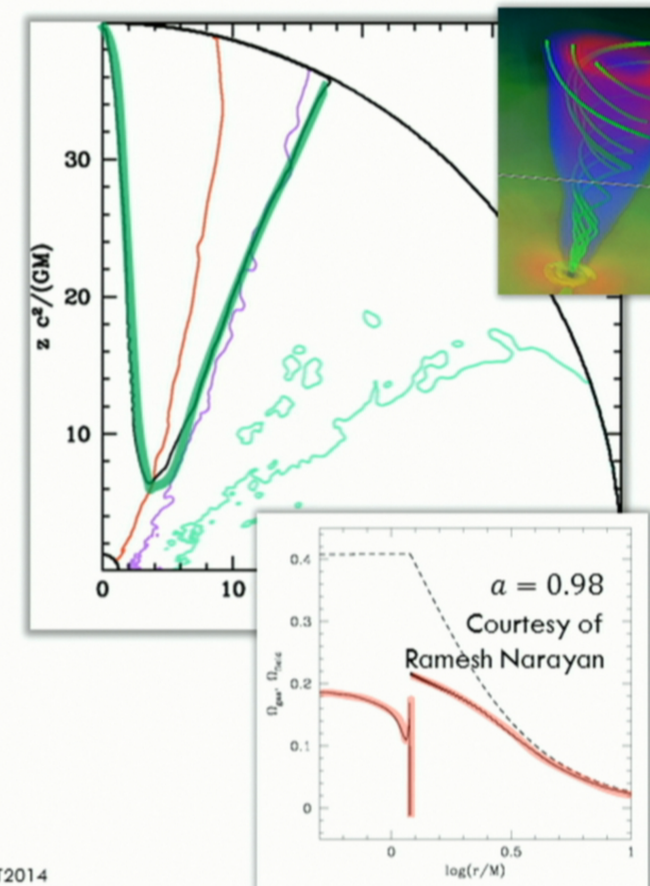

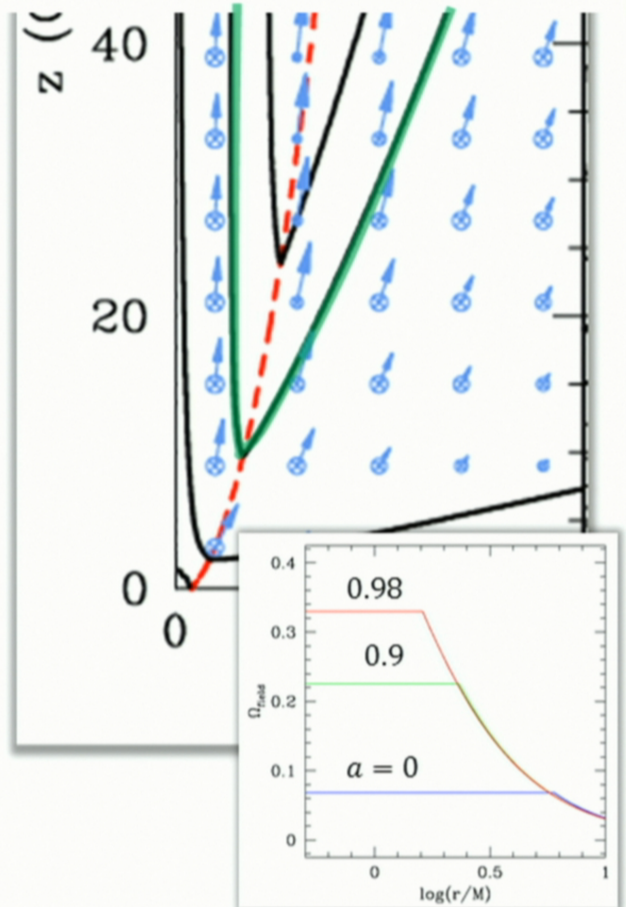

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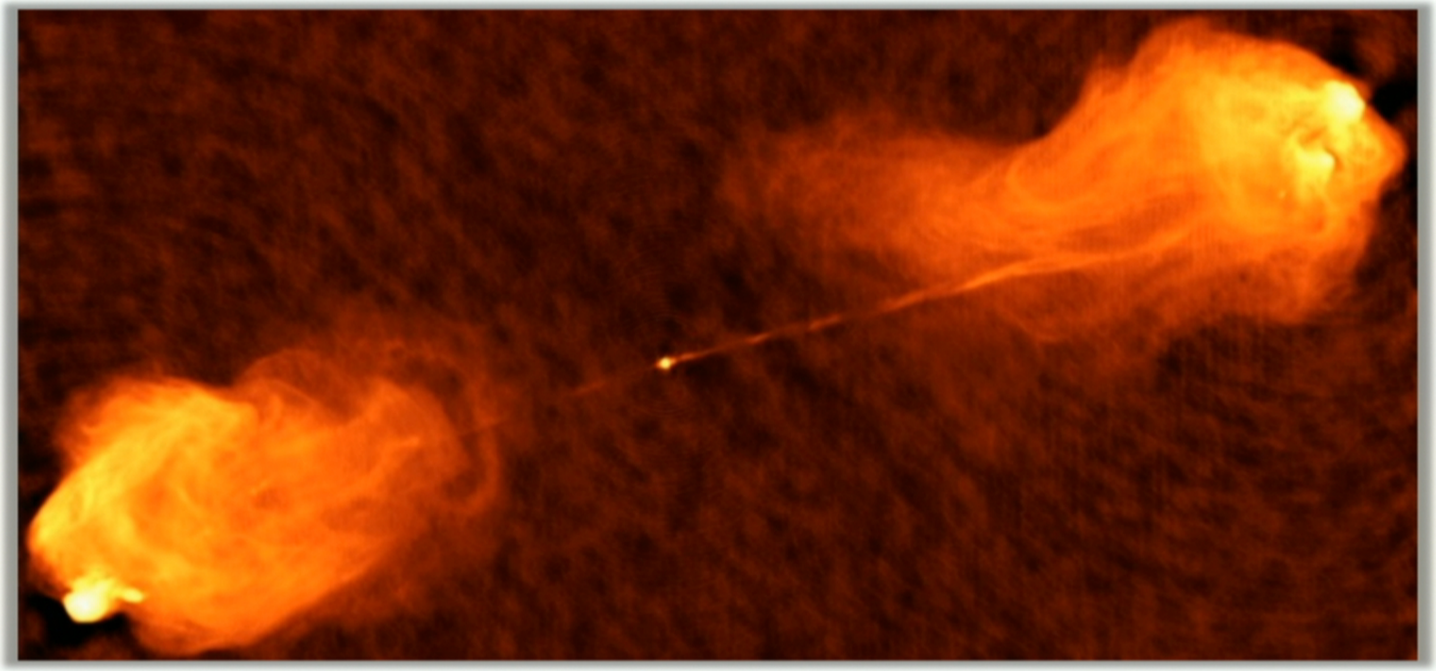
FROM STRUCTURE TO EMISSION: JET PARTICLE CREATION & ACCELERATION



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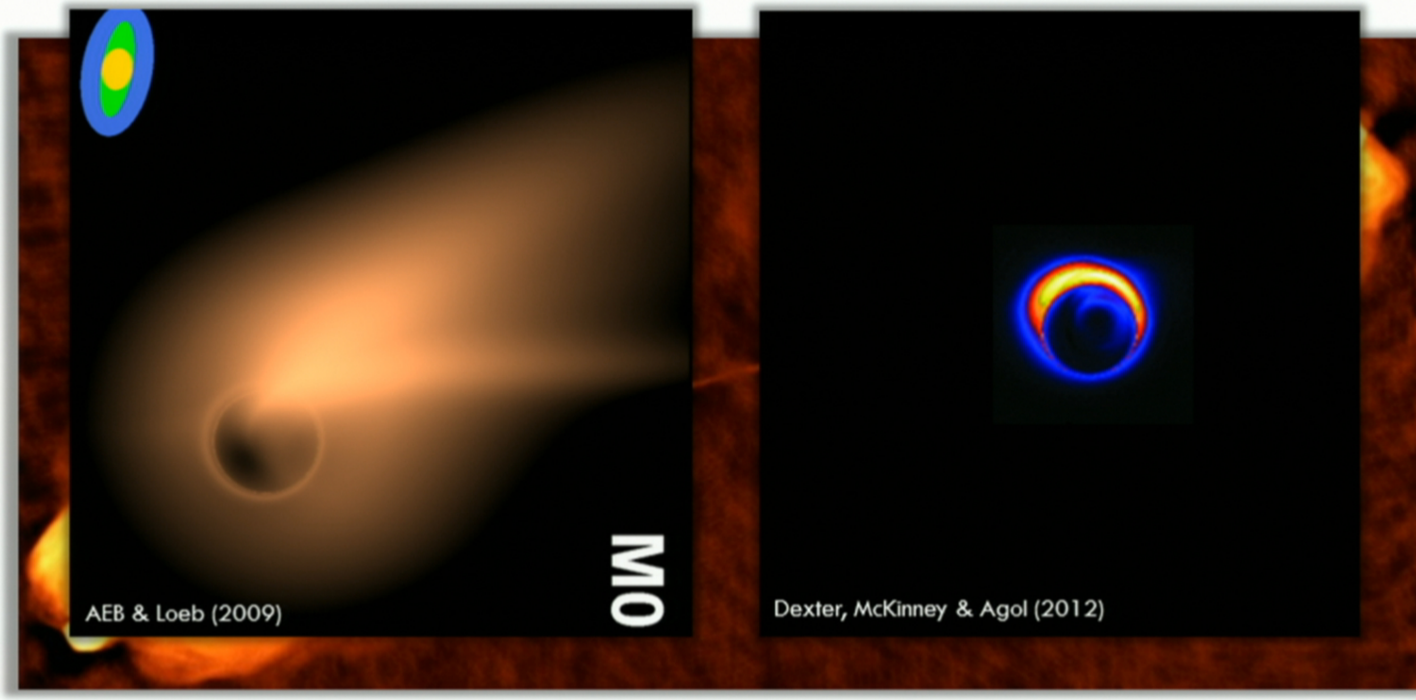

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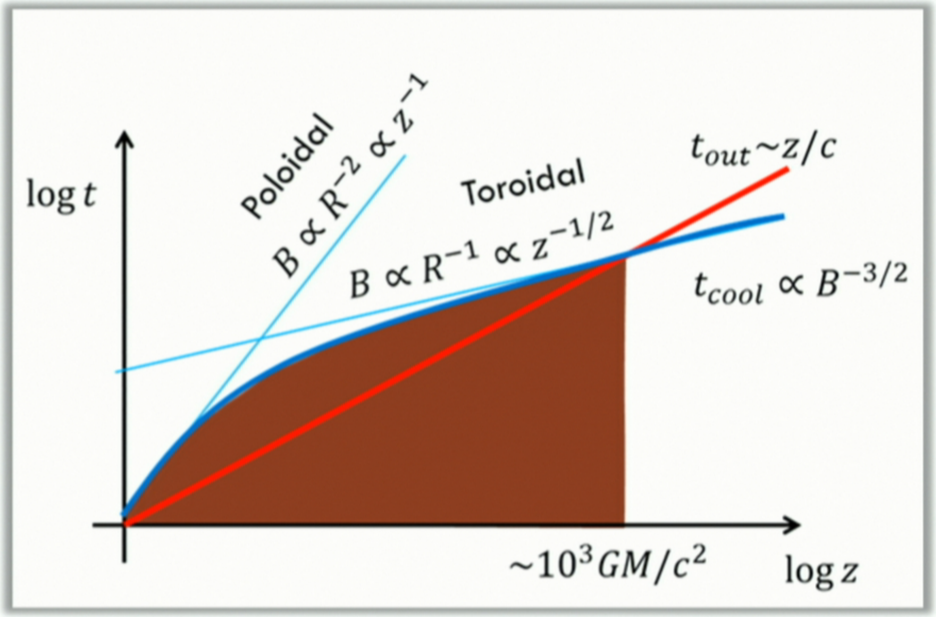
SLOW COOLING LIMIT: CONSERVATION OF NONTHERMAL LEPTONS



- **Particle acceleration smoothed over jet on EHT scales!**
- **Places lower limit on density of nonthermal electrons**
- **Parameterize by typical load radius, and conserve thereafter.**

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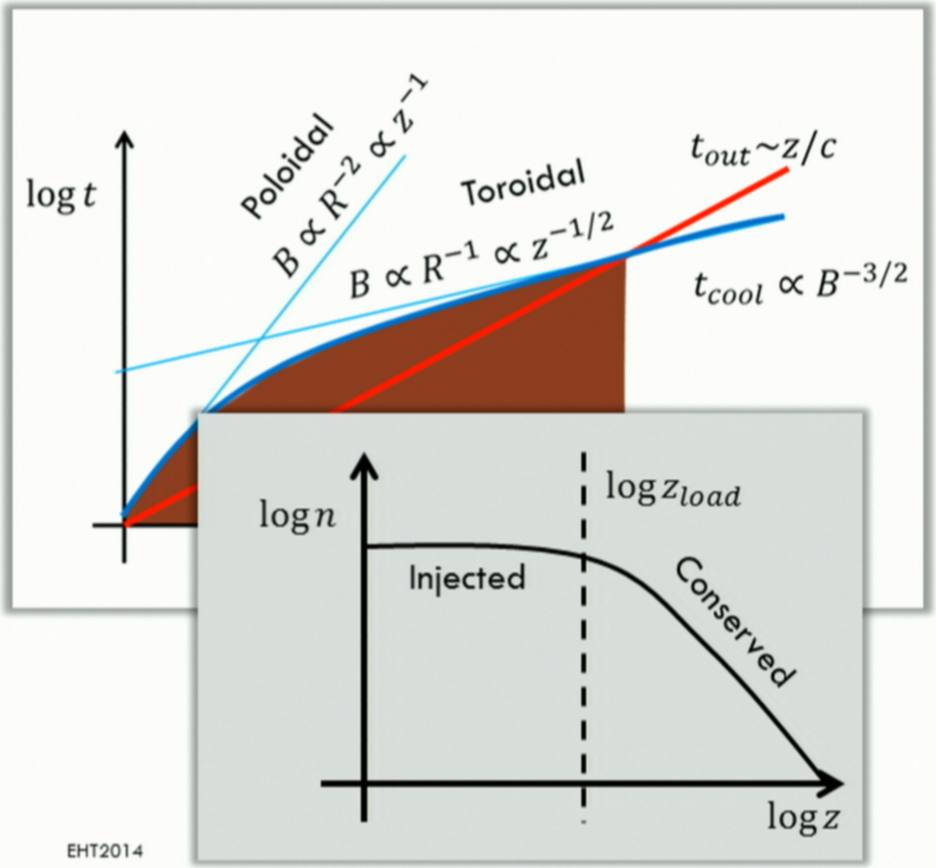

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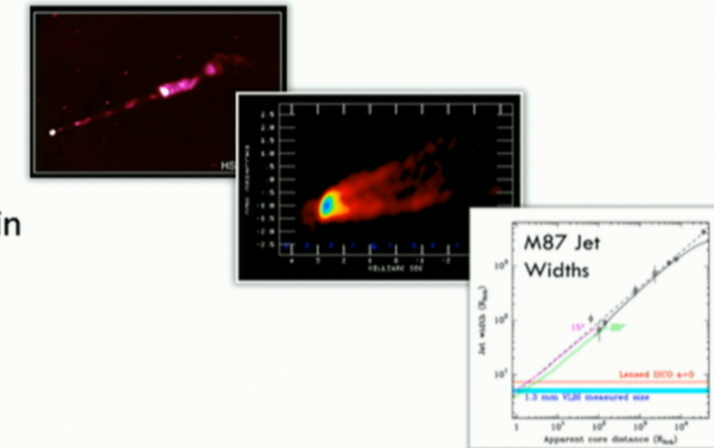
PARAMETERIZED ASTROPHYSICAL JET MODEL

- **Structural Variables**
  - **Jet driving velcoity: $\Omega(r) \leftrightarrow a$**
  - **Particle injection: z_{load}**
  - Large-scale jet mass loading: Γ_{∞}
  - Orientation: Position angle of spin (cross-check!)
  - Confining disk structure: Poloidal field line shape



- **Normalizations & Distribution**
  - Particle densities: n_0
  - Magnetic field strengths: B_0
  - Spectral index: α

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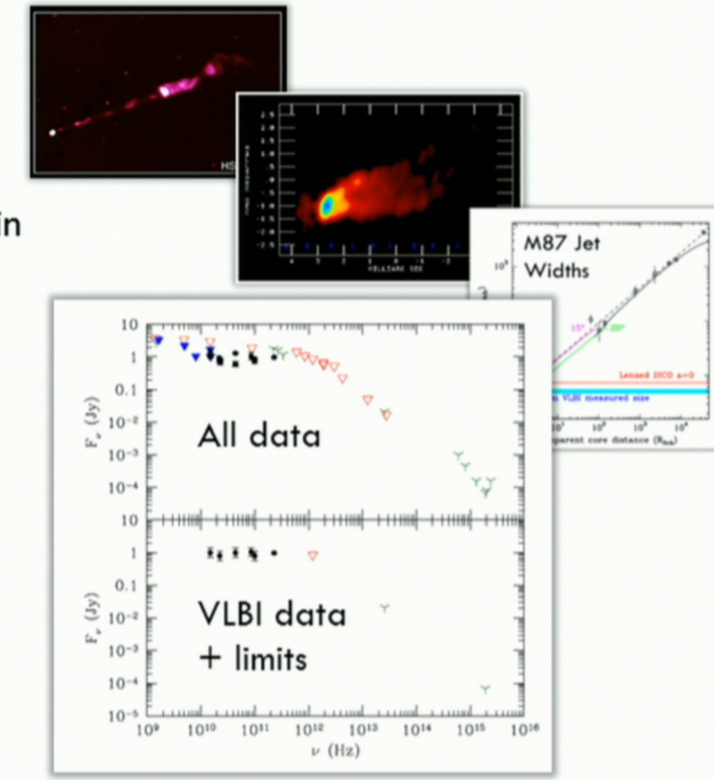

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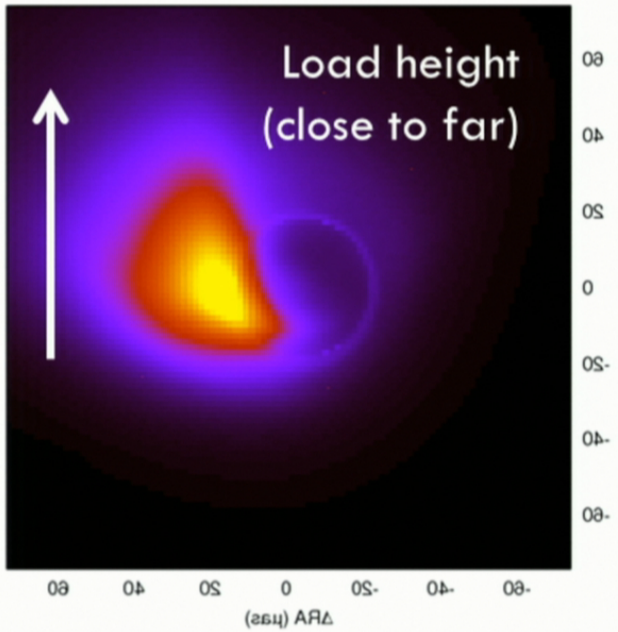
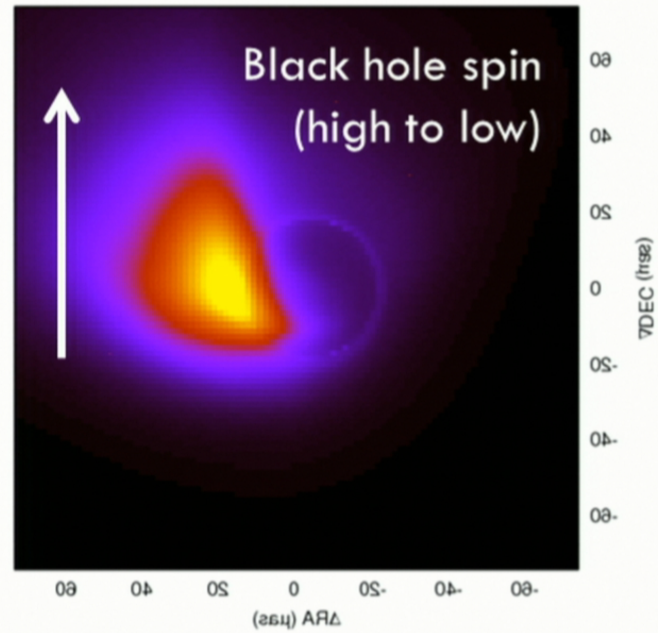
A MODEL FAMILY FOR M87





- **Helical motions → Asymmetric images**
- **Spin & Load height → Image compactness**
- **Counterjet → Shadow**

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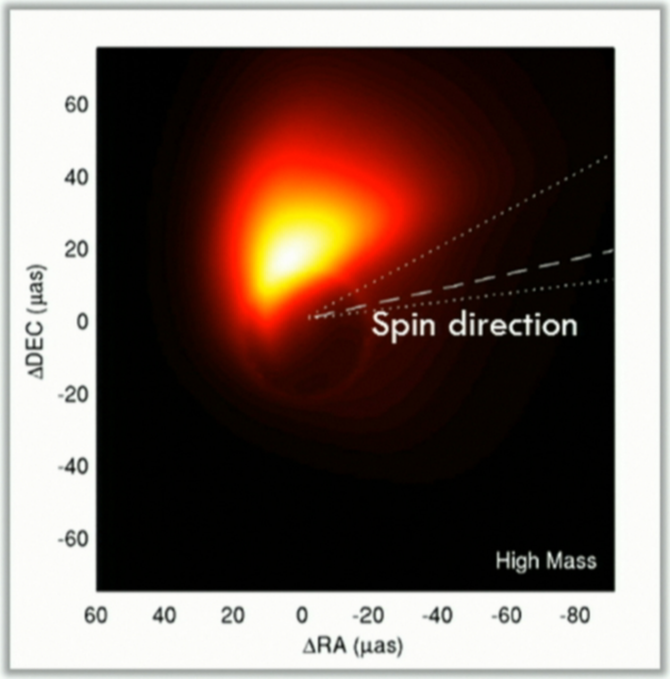
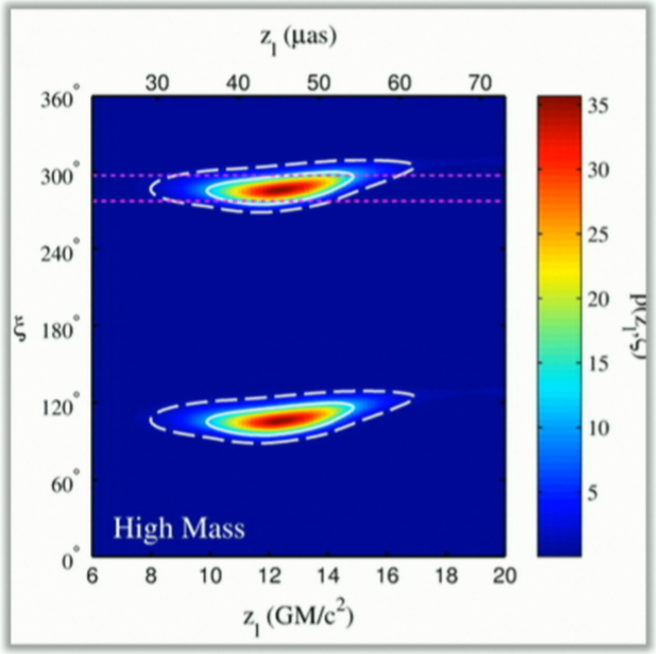
EHT VISIBILITY FITTING RESULTS





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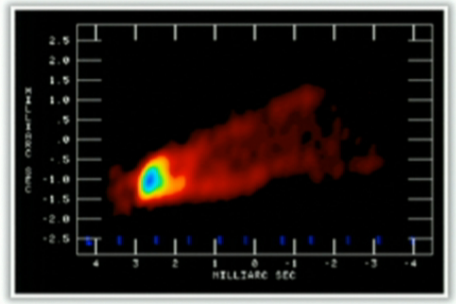

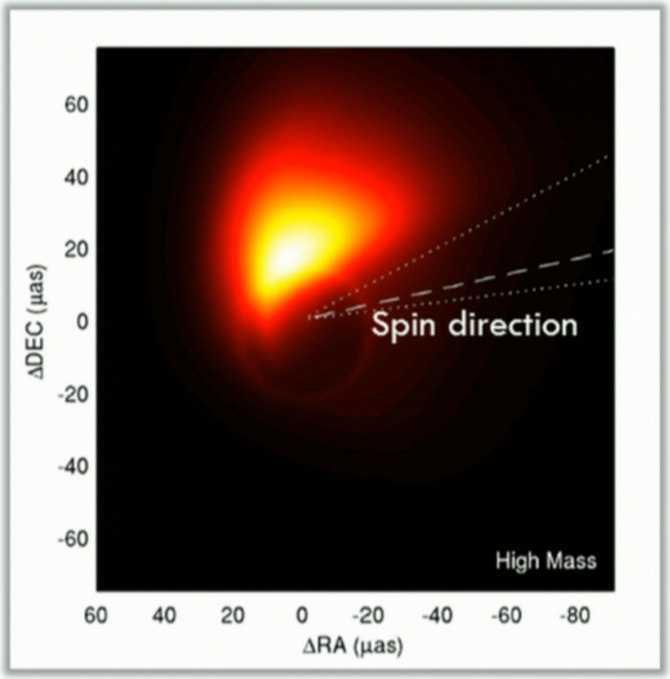

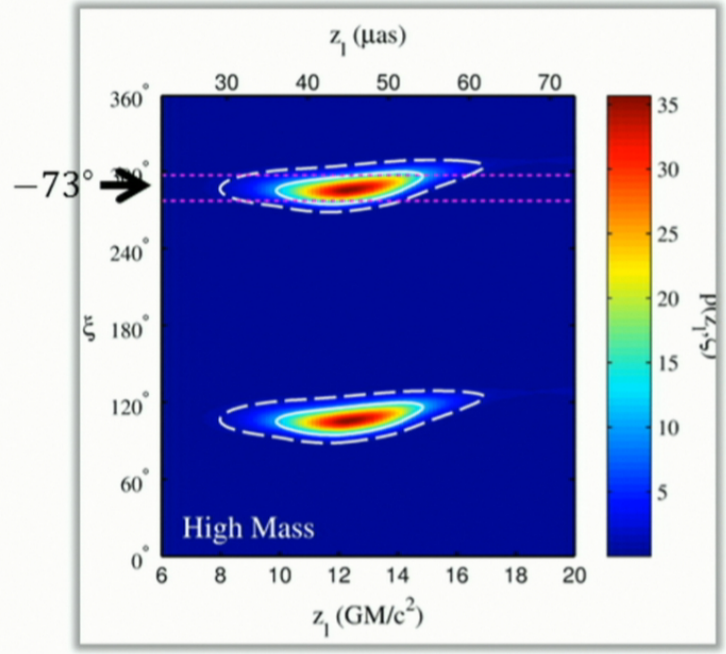

M87's orientation can be reconstructed from mm-VLBI alone!

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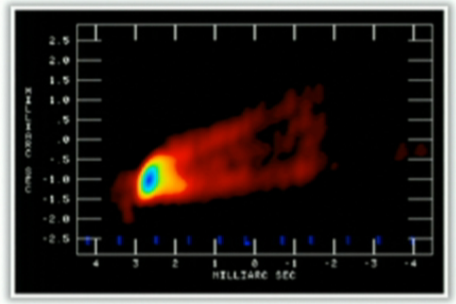
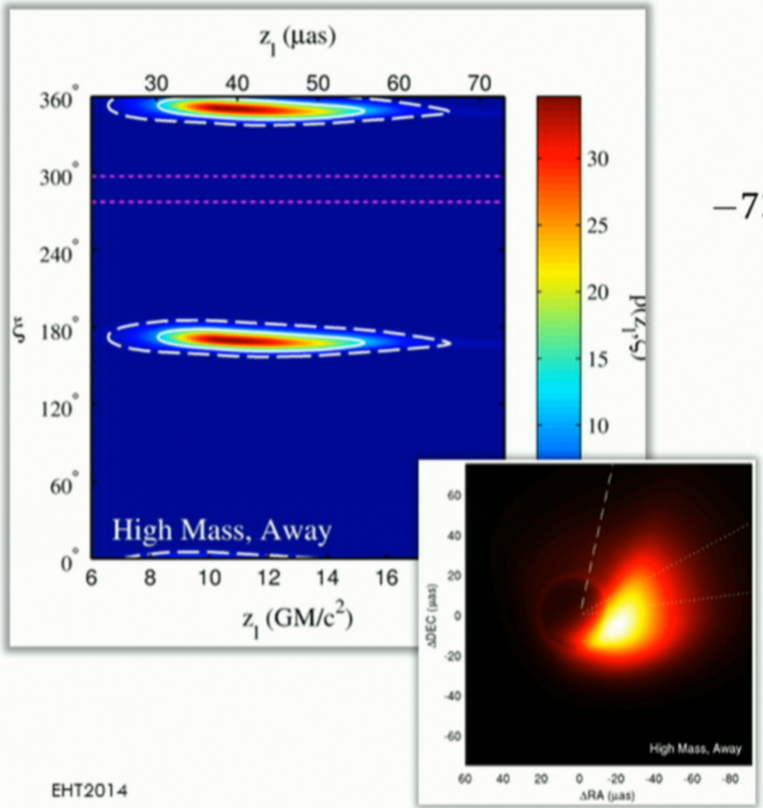
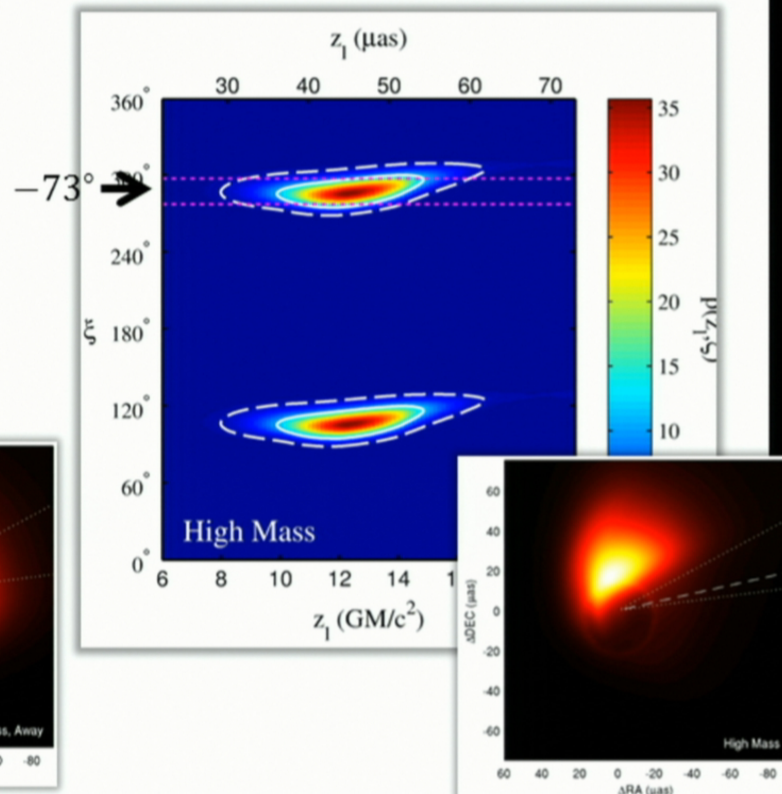
ORIENTATION NOT GENERIC!







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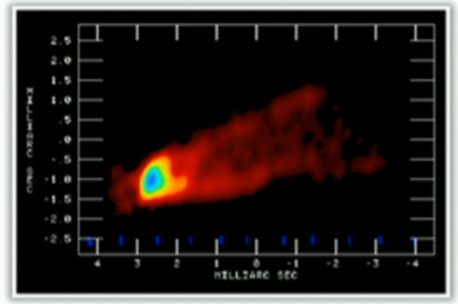

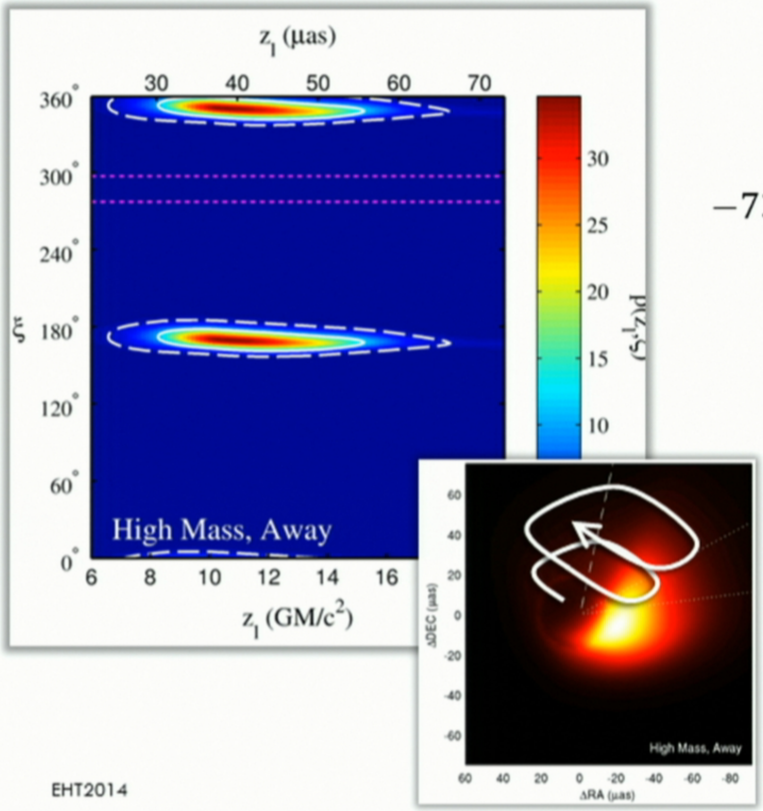

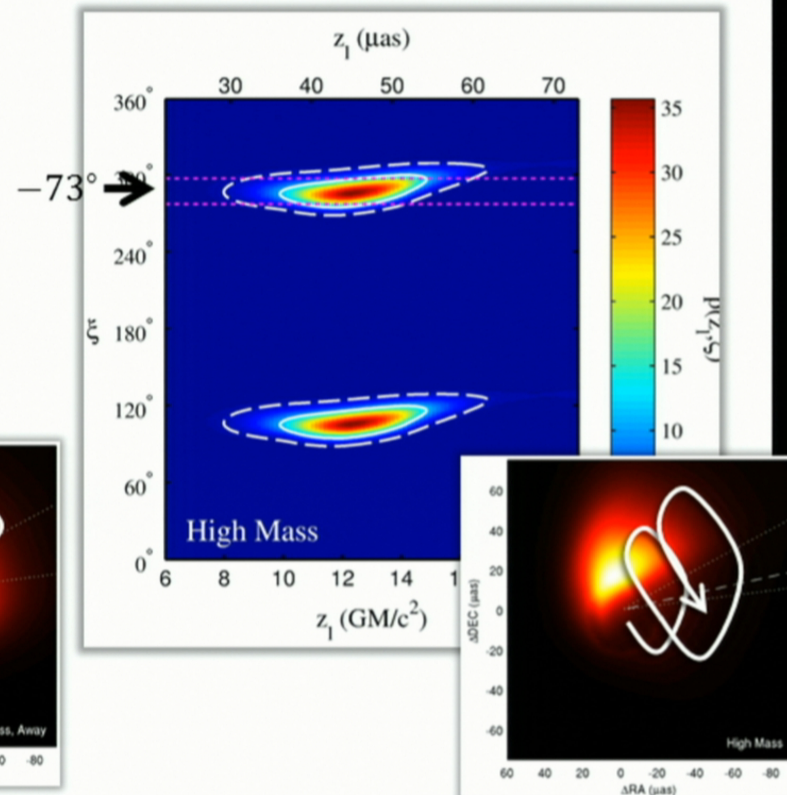

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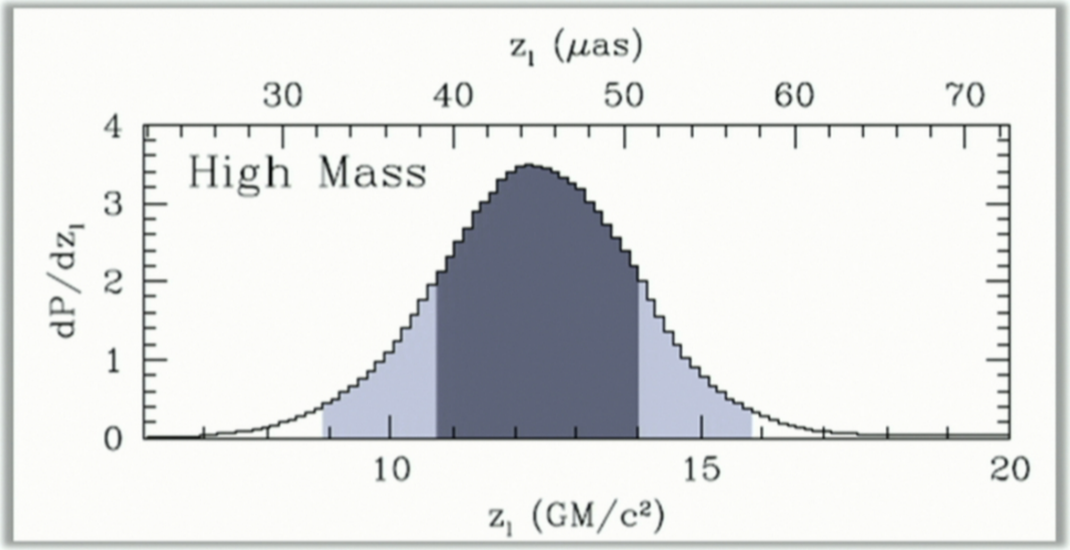
WHERE DOES M87 BEGIN TO SHINE?



What is probably *not* injecting particles

- **Internal shocks**
- **MHD turbulence**
- **Accretion disk**

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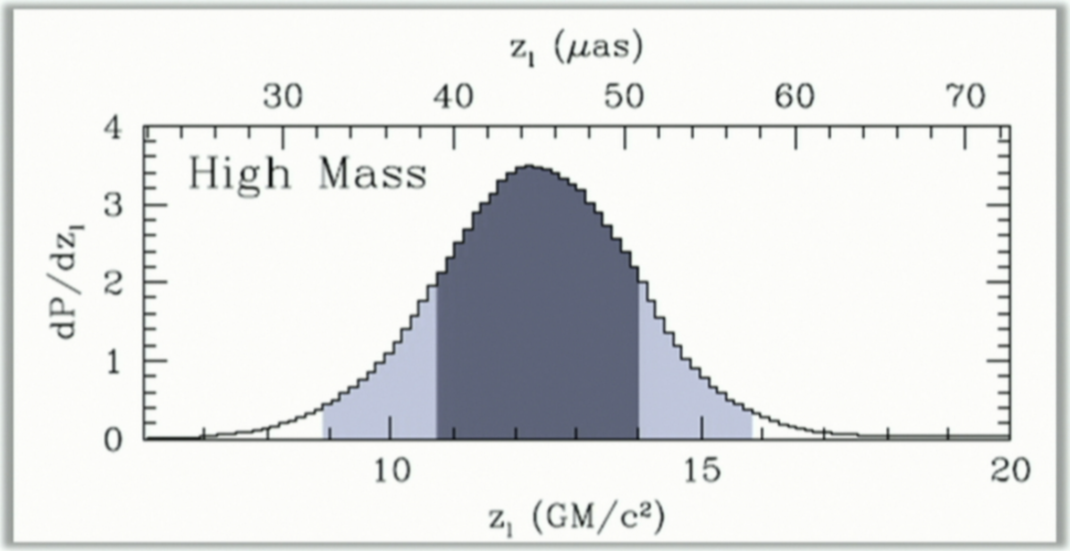

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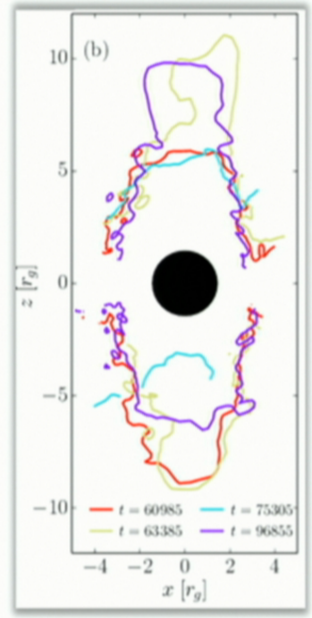
Stagnation Surface



See Sasha Tchekhovskoy's talk!

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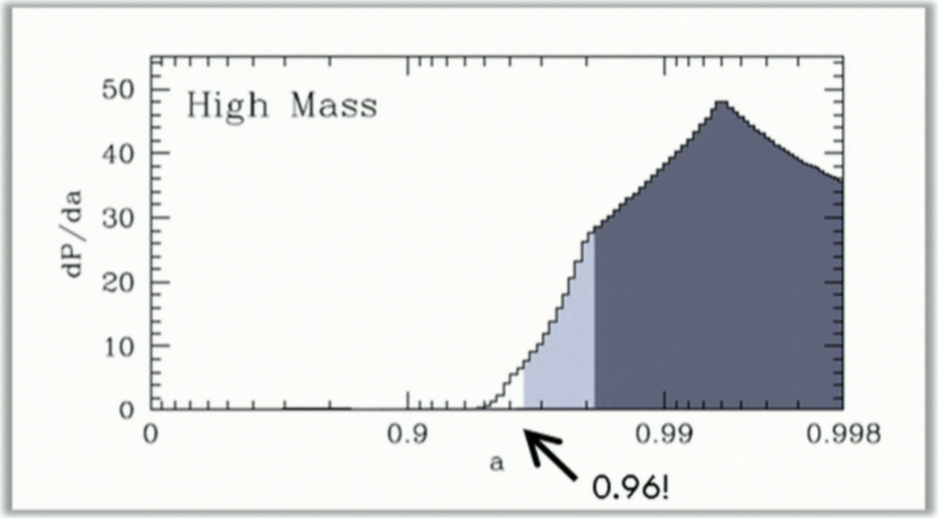
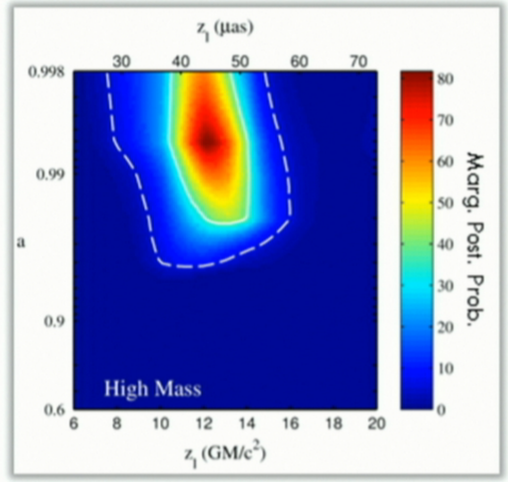
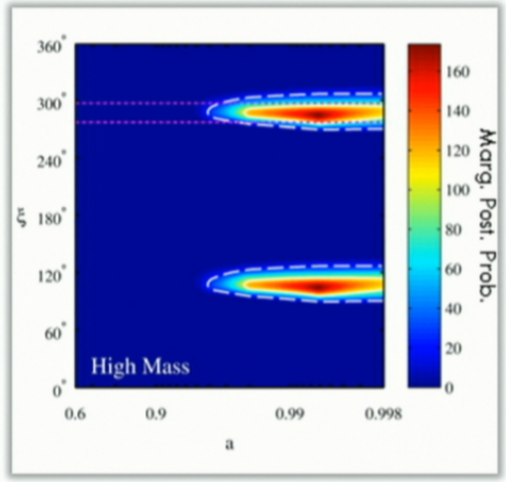
IMPLICATIONS FOR SPIN







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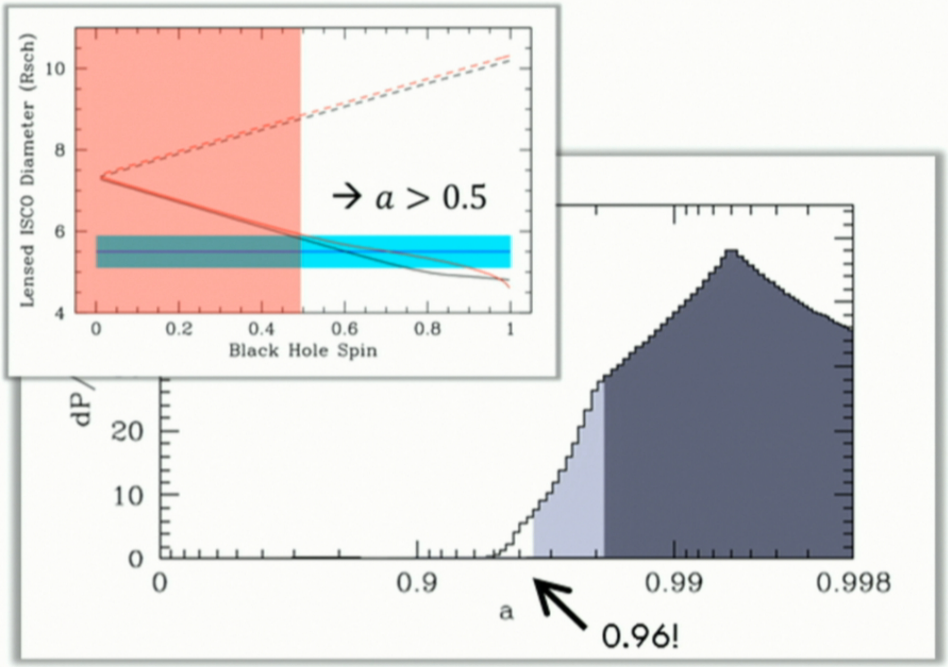

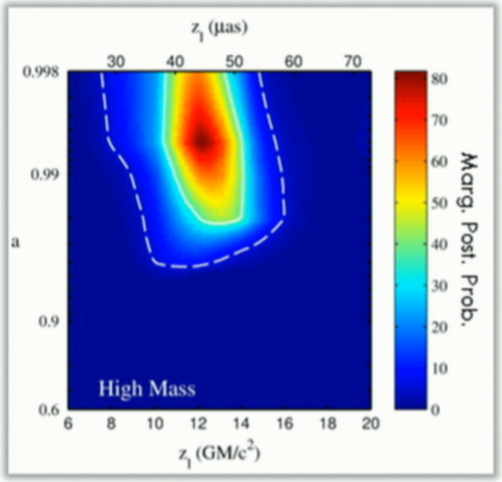

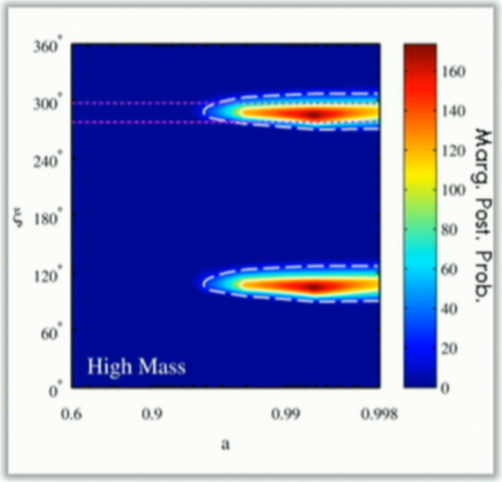

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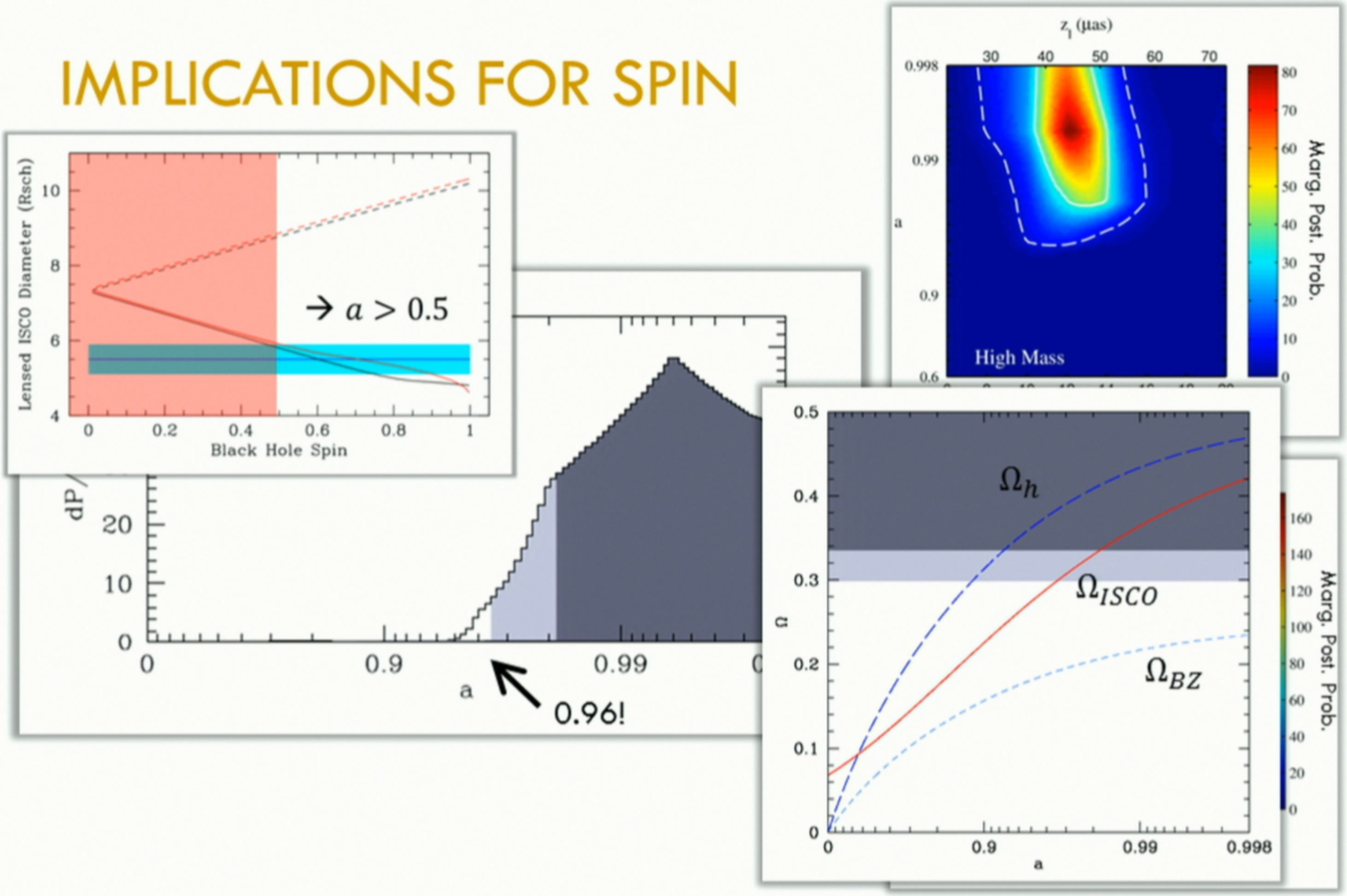
IMPLICATIONS FOR SPIN



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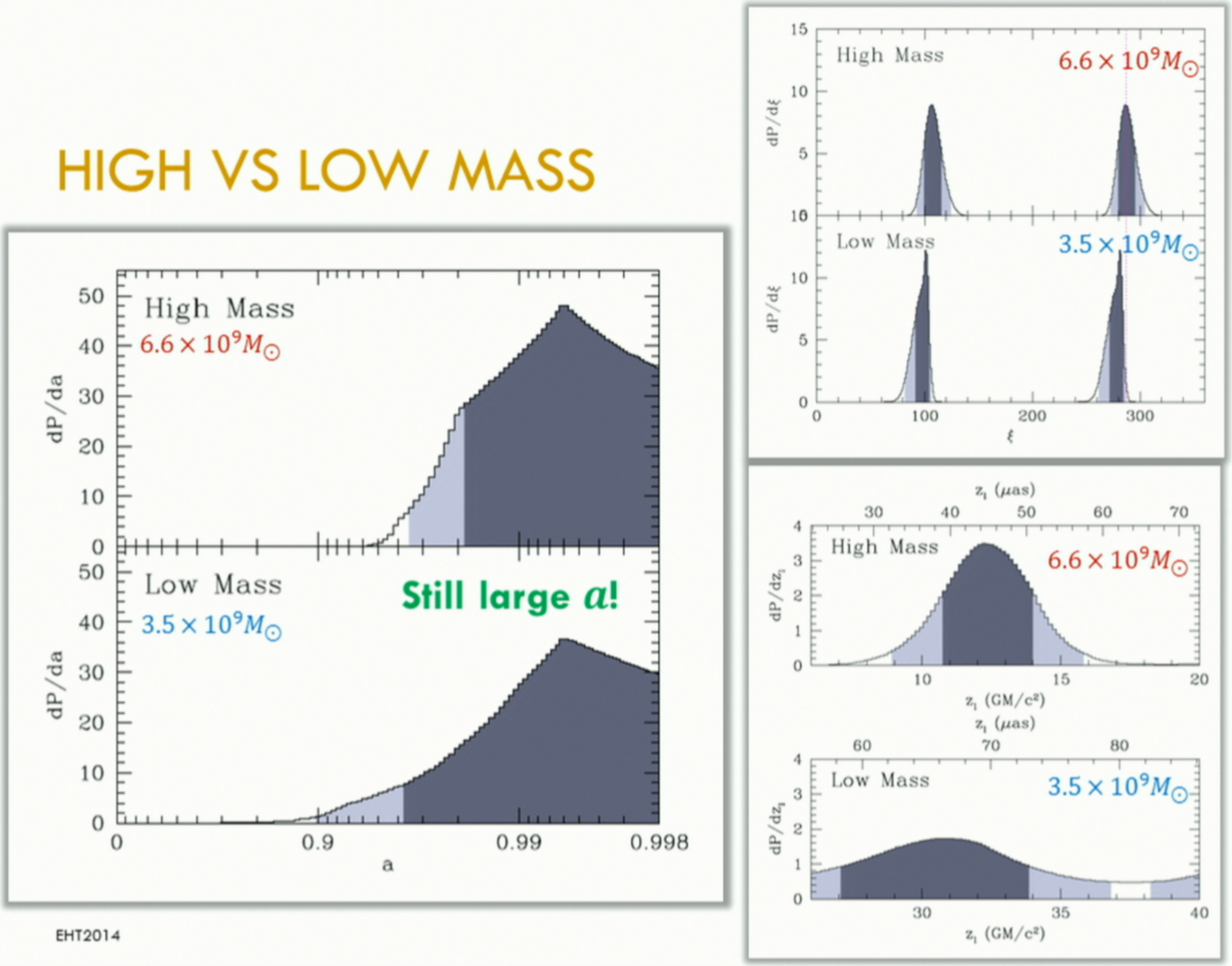
HIGH VS LOW MASS



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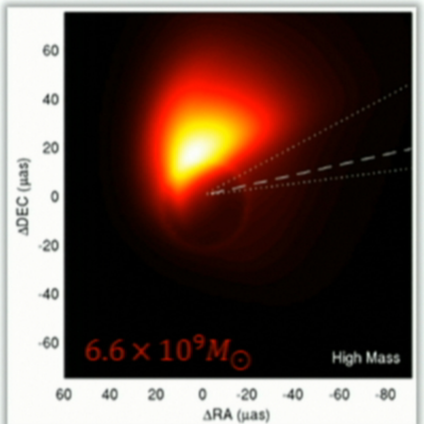
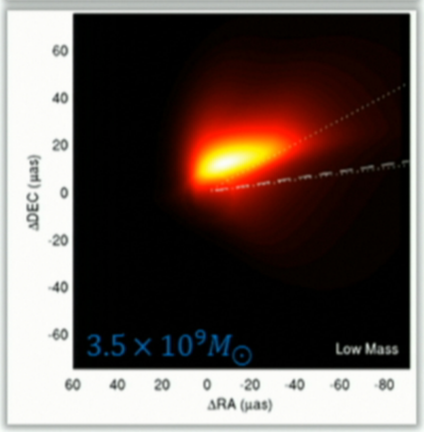
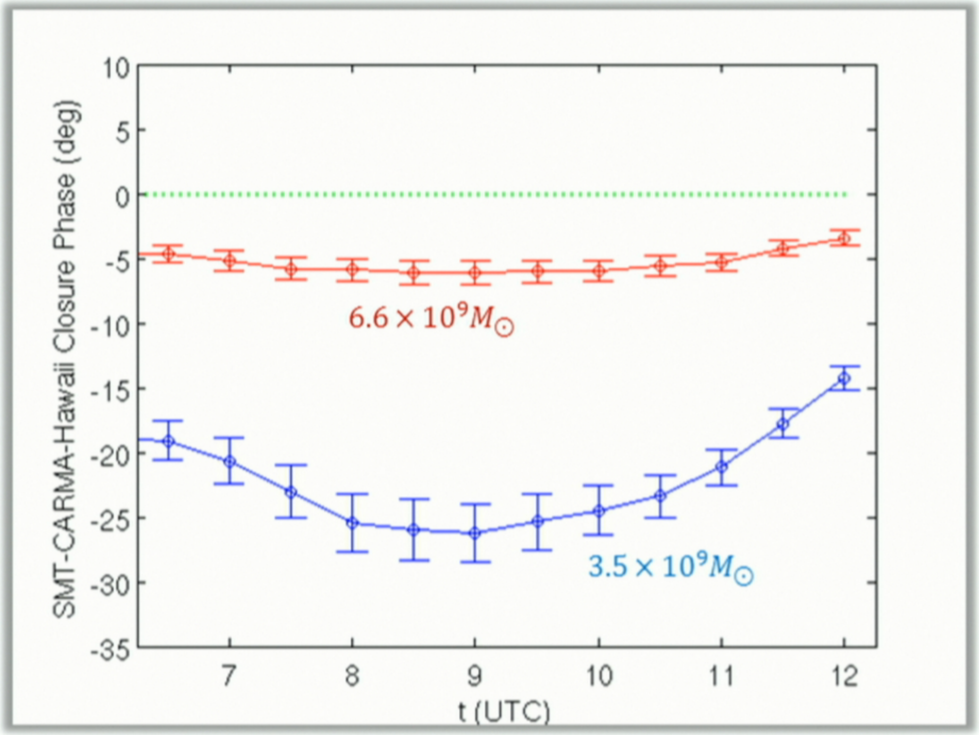
DIFFERENTIATING MASSES

See Kazunori Akiyama's talk!







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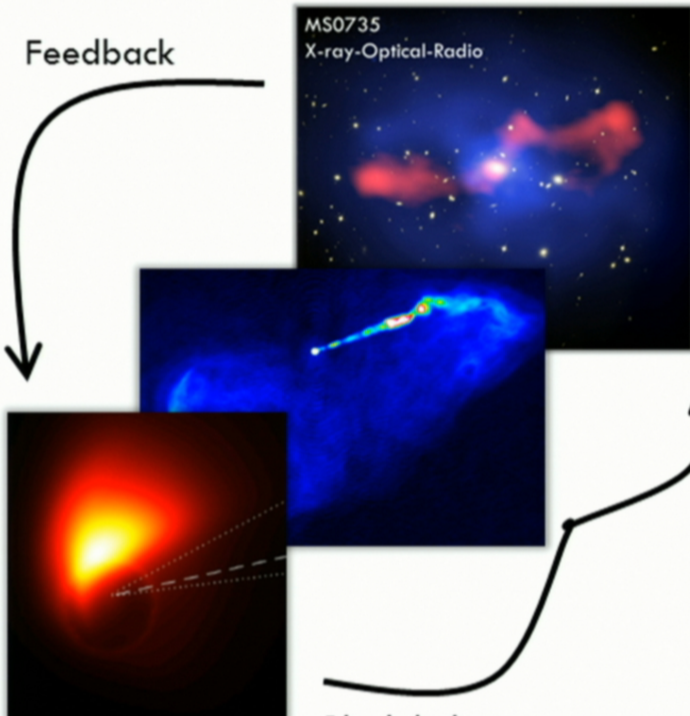
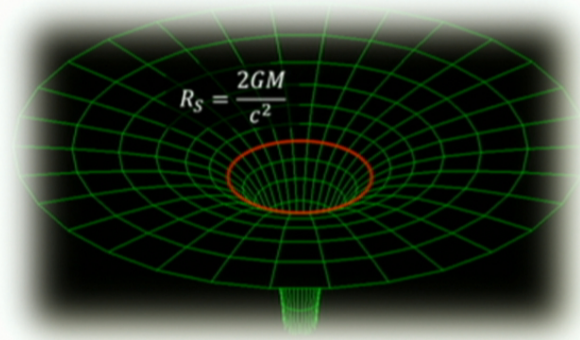
LEVERAGE GAINED FROM VALIDATING EM-LAUNCHED JETS

Feedback



Black hole spin

Evidence for event horizons!
(apparent horizons)



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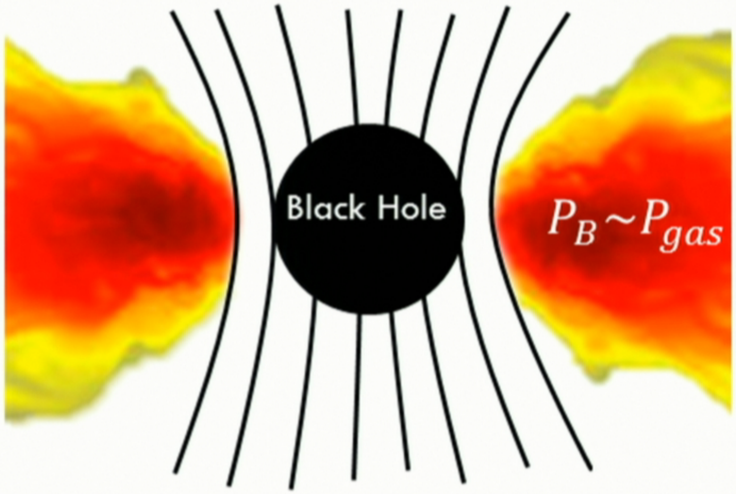
PROBING HORIZONS IN M87



AEB, Narayan, Kormendy, Perlman, Rieke in prep

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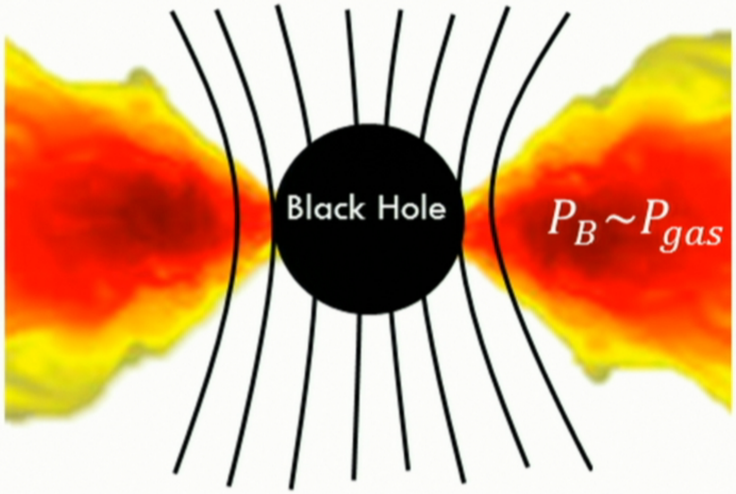

$$L_{jet} \approx \epsilon_{jet} \dot{M} c^2$$
$$\epsilon_{jet} \approx 2$$

AEB, Narayan, Kormendy, Perlman, Rieke in prep

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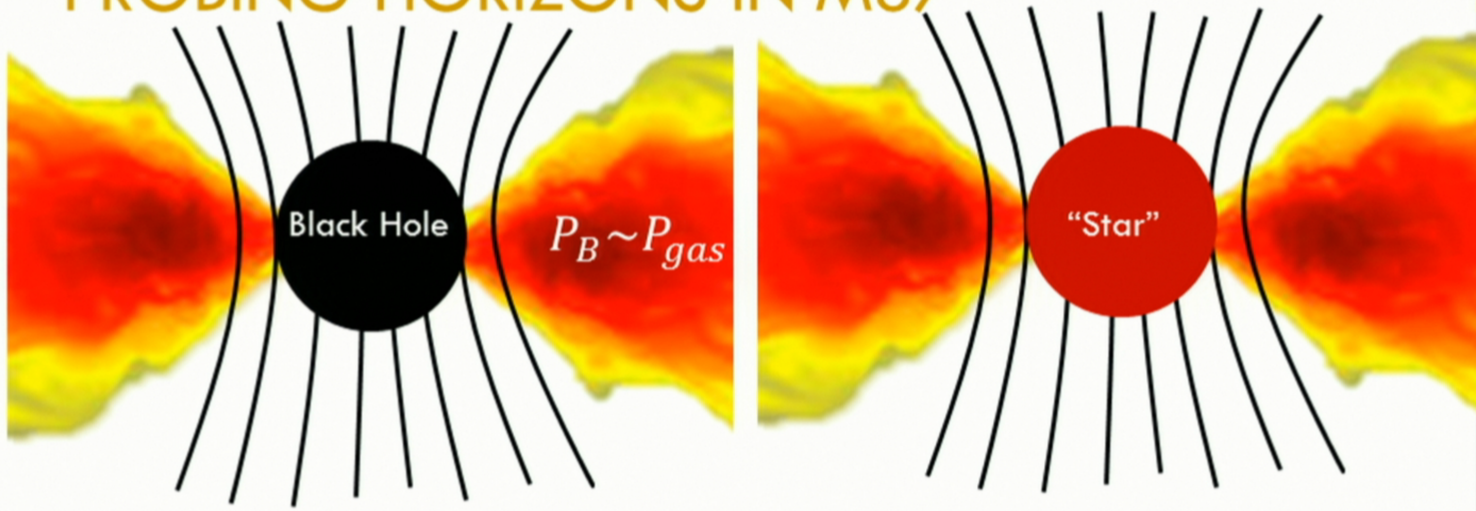

$$L_{jet} \approx \epsilon_{jet} \dot{M} c^2$$
$$\epsilon_{jet} \approx 2$$

$$L_{surf} \approx \dot{M} c^2$$
$$\approx L_{jet}/\epsilon_{jet}$$

AEB, Narayan, Kormendy, Perlman, Rieke in prep

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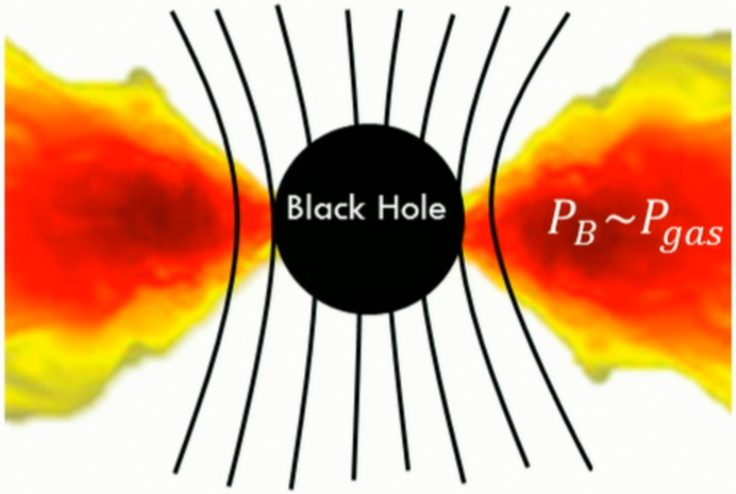
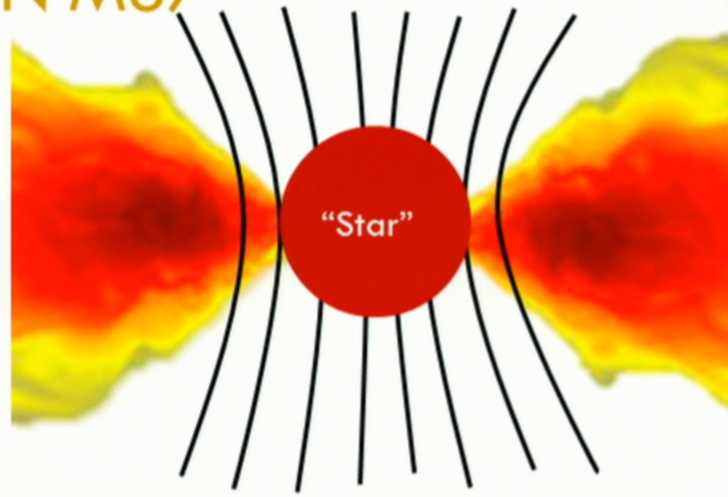
PROBING HORIZONS IN M87





$$L_{jet} \approx \epsilon_{jet} \dot{M} c^2$$
$$\epsilon_{jet} \approx 2$$

AEB, Narayan, Kormendy, Perlman, Rieke in prep

$$L_{surf} \approx \dot{M} c^2$$
$$\approx L_{jet} / \epsilon_{jet}$$

- Compact ($r < r_\gamma$)
- Steady state ($t_{acc} \gg GM/c^3$)

→ ***Thermal!***

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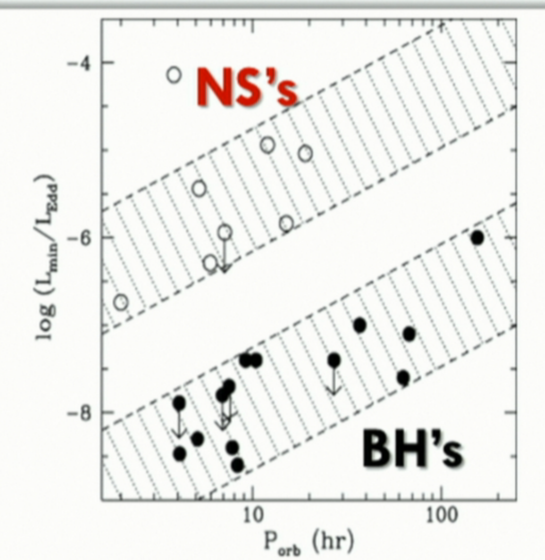
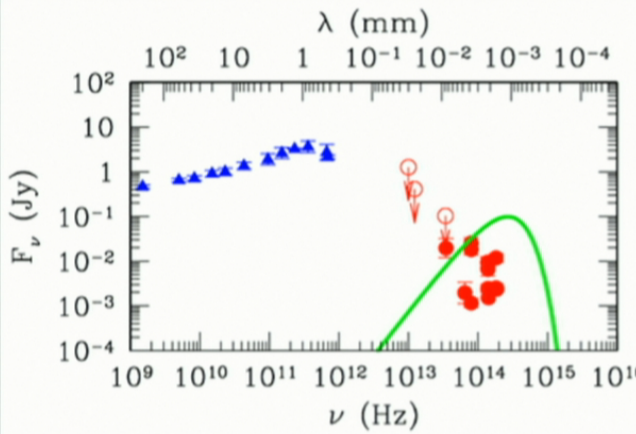
PROBING HORIZONS IN OTHER BLACK HOLES



Narayan & McClintock, New AR (2008)
Garcia et al. (2001), (also, Narayan & Heyl, 2002)

X-ray Binaries



Sagittarius A*

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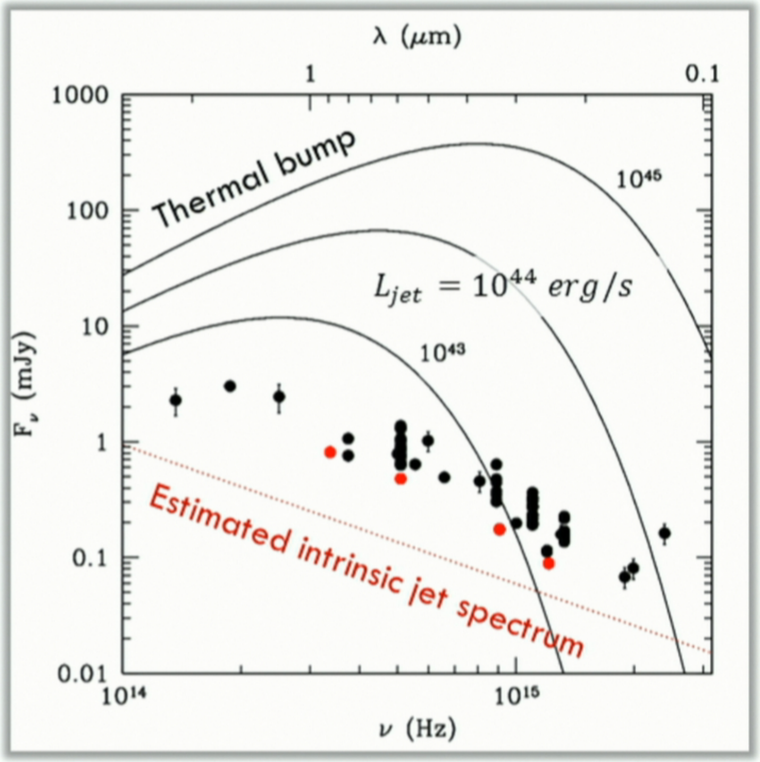
PROBING HORIZONS IN M87



AEB, Narayan, Kormendy, Perlman, Rieke in prep

→ ***A "surface" in M87 has been excluded at $\gg 7\sigma$!***

→ ***Joins Sgr A*!***

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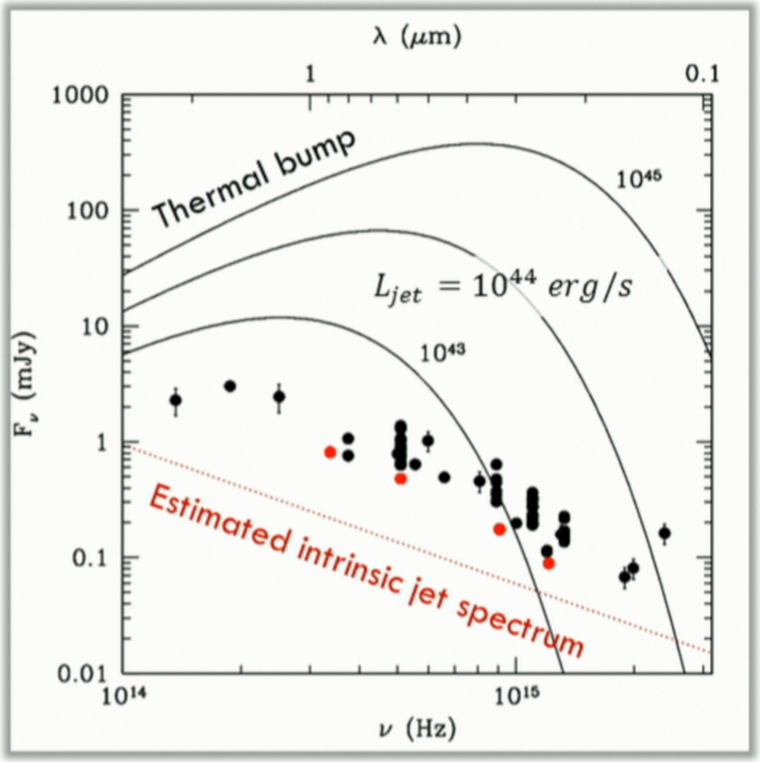
PROBING HORIZONS IN M87



AEB, Narayan, Kormendy, Perlman, Rieke in prep

So, if:

- **M87's jet is EM-driven**
- **M87 is in steady state**
- **The central object is sufficiently compact**

→ *A "surface" in M87 has been excluded at $\gg 7\sigma$!*

→ *Joins Sgr A*!*

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SUMMARY

- Electromagnetically launched jets are highly successful at reproducing the EHT observations of M87
- Regardless of detailed driving mechanism, M87 has very high spin
- Long synchrotron cooling times admit critical simplifications, and implicate global jet features in the origin of relativistic particles (see Tchekhovskoy's talk!)
- High and Low Mass models for M87 have substantively different predictions for closure phases (see Akiyama's talk!)
- Validation of EM-launching models implicates an event (apparent) horizon, making M87 the second source (Sgr A*) for which an explicit argument can be made to date.

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